LEUKOS

The Journal of the Illuminating Engineering Society

ISSN: 1550-2724 (Print) 1550-2716 (Online) Journal homepage: http://www.tandfonline.com/loi/ulks20

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To cite this article: Kevin A. G. Smet (2017): Two Neutral White Illumination Loci Based on Unique White Rating and Degree of Chromatic Adaptation, LEUKOS, DOI: 10.1080/15502724.2017.1385400

To link to this article: https://doi.org/10.1080/15502724.2017.1385400

Published online: 04 Dec 2017.

LEUKOS
https://doi.org/10.1080/15502724.2017.1385400

Two Neutral White Illumination Loci Based on Unique White Rating and Degree of Chromatic Adaptation

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ABSTRACT
In this article, two new neutral loci are presented characterizing the whiteness perception of illumination color of on- and off-Planckian light sources. The two neutral loci are derived based on (1) unique white ratings obtained on a real three-dimensional cube (UW-locus, object mode based) and (2) the degrees of adaptation obtained from a study of chromatic adaptation under neutral and highly colored illuminations (CA-locus, illumination mode based). Equations are presented describing the loci in the CIE *u′v′* chromaticity diagram and in terms of distance from the Planckian locus (Duv) versus correlated color temperature (CCT) and of "degree of neutrality" versus CCT. Although the two neutral loci are very similar in shape, they are not identical, with the UW-locus being approximately a (blue) shifted version of the CA-locus. The latter was in very good agreement with other illumination based neutral white loci reported in the literature, which all have in common negative Duv for lower CCTs and positive Duv for higher CCTs. Like several other lines of white and achromatic points from literature, the UW-neutral locus was located completely below the Planckian locus. The chromaticity associated with the maximum degree of neutrality was for both loci very close to that of the CIE D65 daylight illuminant, suggestive of earlier reports that vision processes such as color constancy and chromatic adaptation, and hence perceived illumination neutrality, are likely conditioned by natural scene statistics.

ARTICLE HISTORY
Received 20 July 2017
Revised 25 September 2017
Accepted 25 September 2017

KEYWORDS
Achromatic locus; blackbody locus; CCT; chromatic adaptation; daylight; Duv; neutral white locus; Planckian locus; unique white; white; whiteness

1. Introduction

In two earlier studies, the chromaticity of "unique white"—that is, appearing neither reddish, greenish, yellowish, or bluish—was investigated in object [Smet and others 2014] and illumination [Smet and others 2015] mode, both under dark adapted conditions. Results of both studies were very similar and unique white (achromatic or neutral appearance) was found to correspond quite well to an elliptical region in color space located slightly below the blackbody locus around a correlated color temperature (CCT) of approximately 6300 K (average of both studies).

The largest axis was orientated along the blackbody / daylight (cerulean [Bosten 2012]) locus, in agreement with several other studies [Beer and others 2006; Bosten and others 2015; Choi and Suk 2016], suggesting that the visual system is tuned to the statistics of natural scenes [Bosten and others 2015; Chauhan and others 2014; McDermott and Webster 2012; Panorgias and others 2012; Pearce and others 2014; Witzel and others 2011]. These larger tolerances for the perception of white along the cerulean line could, for example, be explained by the large natural variation of daylight (and hence, in addition, absolute object colors) along this yellow–blue axis compared to the orthogonal direction. Other examples of such apparent tuning (self-calibration) of the visual system to prevalent environmental conditions are the increased color discrimination and increased degree of adaptation to bluish-to-neutral illuminations reported respectively by Pearce and others [2014] and Smet and others [2017b].

In any case, the white region had a major-to-minor axis ratio of approximately 2.4, which is very similar to the 2.5 for black surrounds found by Bosten and others [2015], but far from large enough to be considered a "line of whites" (achromatic locus) as reported by several other authors [Ohno and Fein 2013; Ohno and Oh 2016; Perz and others 2016; Rea and Freyssinier 2013, 2014]. Both Whitehead [2013] and Smet and others

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[2014] have indicated that such lines are a natural consequence of the way the experiments of these studies have been set up: by determining the most "white"-appearing *Duv* (distance from the blackbody locus [Ohno 2014] in CIE 1960 Uniform Color Space (UCS) diagram) for separate CCTs (cfr. sampling along iso-CCT lines), they ignore differences in absolute whiteness appearance between the CCTs themselves (whites at different CCTs are not necessarily metamers).

Although this approach is not ideal because it throws away potentially valuable information by turning a two-dimensional region into a one-dimensional line, it does have merit from a practical point of view. In lighting science and applications, the chromaticity of the illumination has traditionally been represented by a convenient one-number measure, the CCT, whereby low and high values respectively refer to warm and cold white lighting. In the past, light source manufacturers have typically aimed at producing on- or near-Planckian sources under the assumption that white lighting could only be produced by these type of chromaticities. CCT was therefore a sufficient and simple characterization of light source tint and has been adopted in various standards and regulations (for example, National Electrical Manufacturers Association [2015] and EPA [2016]).

However, advances in solid state lighting and lowering prices have made full-color-tunable or white-tunable light sources and luminaires (and more generally spectrally tunable) ever more prevalent without clear and unambigous guidelines on what type of illumination tint is most neutral, natural, or preferred at various CCTs. Although there have been quite a few investigations (for example, Chauhan and others [2014]; Dikel and others [2014]; Feltrin and others [2017]; Helson and Michels [1948]; Honjyo and Nonaka [1970]; Hurvich and Jameson [1951]; Kuriki [2006]; Masuda and Nascimento [2013]; Priest [1921]; Smet and others [2011, 2014, 2015]; Valberg [1971]; Walraven and Werner [1991]) on whiteness perception for on- (or near-)Planckian chromaticities (unfortunately often with ambiguous results; for a short review the reader is referred to Smet and others [2014]), systematic studies of more off-Planckian sources are limited [Dikel and others 2014; Li and others 2016; Masuda and Nascimento 2013; Wang and Wei 2017; Wei and others 2016]. This lack has spurred a number of studies, such as the ones mentioned above [Li and others 2016; Ohno and Fein 2013; Ohno and Oh 2016; Perz and others 2016; Rea and Freyssinier 2013, 2014], to specifically characterize the optimal value—in terms of neutrality, naturalness, and preference—of the "missing" second dimension (*Duv*) for separate CCTs. The results of the off-Planckian chromaticity studies can be summarized as follows. Rea and Freyssinier [2013], determining for each of six different CCTs (2700 K–6500 K) the most *neutral*-appearing *Duv* from among seven presented in an illuminated cube setup, found a line of whites with positive *Duv* (above Planckian) and negative *Duv* (below Planckian) for CCTs respectively larger and lower than approximately 4000 K. These results were confirmed by a study of Li and others [2016], who randomly presented 25 lighting conditions in a real room setup and had observers assess white percentage on a 0%–100% scale and whiteness perception and white preference on seven-point categorical scales. Choi and Suk [2016], investigating whiteness perception on displays for 97 different stimuli (seven *Duv* levels for 15 CCTs ranging from 2500 K to 20,000 K), reported finding a region of whites at around 7300 K and positive *Duv* values.

The above three experiments were contradicted by Ohno and Fein [2013] and Ohno and Oh [2016], who found all negative *Duv*s across the entire range of investigated CCTs (2700 K–6500 K) using a similar experimental technique as Rea and others [2015] but instead determining the most *natural Duv* from six levels for 4 different CCTs. The most natural *Duv* was in both experiments fairly constant (approximately −0.016) across the investigated CCT range, with the 2016 experiments showing a slightly nonlinear trend with a maximum *Duv* of −0.014 at 3500 K. Experiments were conducted in a real room setting populated with various colored objects. As pointed out by Smet and others [2015] and more fully explored by Wei and Houser [2016] in simulations, chromaticity might have not been the only driving force in the obtained *Duv* values in the 2013 study but could have been confounded by effects of color rendition. However, the 2016 experiment, designed to minimize the differences in relative gamut of each of the lighting settings, confirmed the 2013 results. Wang and Wei [2017] noted that despite the improved color gamut consistency in the 2016 experiment, the high color gamut and color fidelity indices of the illumination settings associated with negative *Duv* could still have affected the results. In a pilot study, with carefully designed lighting settings that have similar fidelity, color gamut (cfr. R_f and R_g measures of IES TM-30-15 [IES 2015]) and color gamut shape, they investigated the preferred *Duv* for 3000 K and 6500 K. Both settings showed negative *Duv* values, as in Ohno and Fein [2013] and Ohno and Oh [2016], but with a trend for the 6500 K *Duv*s to move closer to the Planckian locus: *Duv* at 3000 K: −0.01 to −0.02; 6500 K: 0 to −0.01. *Negative* Duv values were also found by Perz and other [2016], who investigated the most *neutral Duv* for three CCTs (2700 K - 5000 K) using a viewing box setup containing a single white sheet of paper The line of whites was, however, markedly closer and quite parallel to the Planckian locus (*Duv*s ~ −0.006). In a free setting experiment, Dikel and others [2014] also found that observers preferred light source spectral power densities with a negative *Duv* (mean ~ −0.0139). They also reported very high observer variability for CCTs ranging from 2850 K to 14000 K with a median of approximately 4400 K. Negative *Duv* values were further confirmed by Smet and others [2014, 2015], who found that, at least under dark adapted conditions using real objects and a data projector as light source, the most neutral white corresponds to a (region of) chromaticity of approximately 6300 K with negative *Duv* (~ −0.007). In these latter two studies, unique white or "neutrality" was investigated using an achromatic setting and a rating method.

Though both studies gave similar results and provided the location and extent of a white or neutral region in color space, the rating experiment provided additional information on the "degree of neutrality" as a function of chromaticity, which was modeled by a bivariate Gaussian function in CIE 1976 $u'v'$ coordinates and reported in Smet and others [2014].

Because CCT and *Duv* are the more commonly used coordinates in lighting research and a line of whites or an achromatic locus has proven to be of practical interest in lighting development and application, this article develops a practical working model for the UW-neutral locus and one for the CA-locus in terms of CCT and *Duv*. The article further investigates how the UW-locus corresponds to the CA-locus that is developed based on the modeled "degree of adaptations" obtained by Smet and others [2017b] while investigating chromatic adaptation using memory color matches under colored illumination. Given that the function of chromatic adaptation is to discount the color of the illuminant, the perceived neutrality of the illumination should be directly proportional to the degree of adaptation, thereby providing an alternative to determining illumination whiteness or neutrality. This method is not dependent on direct whiteness judgements, nor is it biased by possible confounding effects related to the color rendition properties of the illumination.

2. Derivation of two new neutral loci

In the following sections, two neutral loci are derived. One, the *UW-neutral locus*, is based on the unique white ratings under dark adapted conditions published by Smet and others [2014]. The other, the *CA-neutral locus*, is based on psychophysical data on the degree of chromatic adaptation obtained in a study of chromatic adaptation to neutral and colored illuminations [Smet and others 2017b]. First, an overview is presented of the concept, experiments, and psychophysical data of these two studies. Secondly, the two new neutral loci are derived, with equations for representation in the CIE $u'v'$ chromaticity diagram and in a *Duv* versus CCT graph, as well as an equation to calculate the degree of neutrality on the loci as a function of CCT.

2.1. Psychophysical data from literature

2.1.1. Neutral white ratings from Smet and others [2014]

The degree of neutrality of a "white" cube viewed under dark adapted conditions was investigated in a rating experiment for three different cube luminance levels: 200 cd/m^2, 1000 cd/m^2, and 2000 cd/m^2 (corresponding to approximately 740 lx, 3700 lx, and 7400 lx). Fifty-nine chromaticities uniformly distributed (in the CIE 1976 u'_{10},v'_{10} diagram; see also figure 2 in Smet and others [2014]) around the blackbody locus and extending slightly beyond the Class A white region (CIES004/E-2001 [CIE 2001]) of the CIE were presented in a random order to a panel of 13 color-normal observers. Stimuli were formed by projection of light of a data projector onto a spectrally near-"white" cube (spectrally flat spectral reflectance with $\beta \approx 0.85$) covering a field of view of 5.7°. Observers were dark adapted and were asked to rate the presented stimulus chromaticity in terms of its neutrality on a 0–10 scale. Each of the 59 stimuli were spectrally measured and converted to CIE 1976 u'_{10},v'_{10} chromaticity coordinates. The results of the three rating experiments for the unique white region's location, size, and orientation showed good agreement with one another and with those from achromatic settings obtained in that same study [Smet and others 2014] (and in a follow-up study; Smet and others [2015]) and indicated an underestimation (respectively, overestimation) of high and low CCTs appearing as white by the CIE Class A white region. A bivariate Gaussian model was fitted to the rating data for the three luminance levels and one where these three data sets were pooled (referred to as the *luminance invariant* case). The unique white rating model $R(u'_{10}, v'_{10})$ is given by

$$R(u'_{10}, v'_{10}) = a_6 \cdot \exp\Big(-0.5\Big(a_1(u'_{10} - a_3)^2 + a_2(v'_{10} - a_4)^2 + 2a_5(u'_{10} - a_3)(v'_{10} - a_4)\Big)\Big), \tag{1}$$

with a_1–a_6 parameters (see table V in Smet and others [2014]) describing the height, shape, location, and orientation of the bivariate Gaussian function in the CIE 1976 u'_{10},v'_{10} chromaticity diagram.

2.1.2. Modeled degrees of chromatic adaptation from Smet and others [2017b]

Chromatic adaptation to neutral and colored illuminations [Smet and others 2017a, 2017b] was investigated using a novel experimental method involving memory color matches of five real familiar objects.

The familiar objects covered different regions of the hue circle: a red tomato, a yellow lemon, a green apple, a blue Smurf, and a gray cube ($\beta \approx 0.4$).

The background scene (field of view ≈ 50°) was spectrally flat and populated with spectrally neutral objects of varying luminance factor to increase scene realism, which has been reported to have a positive impact on color constancy [Foster 2011]. Colored objects were specifically not included to avoid biasing the background chromaticity. Object color and background color were generated or adjusted by adding spatially selective colored light with a calibrated data projector (the same one that was used in the unique white rating experiments). In other words, the object and background scene were illuminated with different lightings by setting the pixels associated with each to different red–green–blue values. A schematic of the experimental setup, a view of the setup from the observer point of view, and the spectra of the red–green–blue primaries are illustrated in Fig. 1.

For this study, the background luminance level was kept constant at 760 cd/m^2 (approximately 2600 lx) but varied in color (due to changing projector illumination) from eight near-Planckian chromaticities, corresponding to CCTs ranging between 2000 K and Inf K, to five high chroma values (red, yellow, green, blue, and magenta; see Fig. 1 in Smet and others 2017b].

In the experiments, 23 observers (with at least 10 per familiar object) were asked to adjust the color appearance of the familiar object presented on a spectrally neutral background illuminated by one of the 13 illumination conditions until it matches what they remember the object looks like in reality (that is, matching from long-term memory). Using the arrow keys of a regular keyboard, observers could adjust the object chromaticity by moving in the CIE $u'v'$ chromaticity diagram. Each object was presented for each illumination condition four times, each with a different starting chromaticity to minimize starting bias. Before starting each match, observers were allowed to adapt for 15 s (50% of the steady-state adaptation is reached within the first few seconds; Fairchild and Reniff [1995]) and by the time the observer finished a match (taking at least 1 min), approximately 90% of the steady-state adaptation level for that adapting chromaticity would have been reached.

After a satisfactory match, the memory color was spectrally recorded and converted to CIE 1964 tristimulus values.

For each pair of illumination conditions, corresponding color data sets were obtained from the

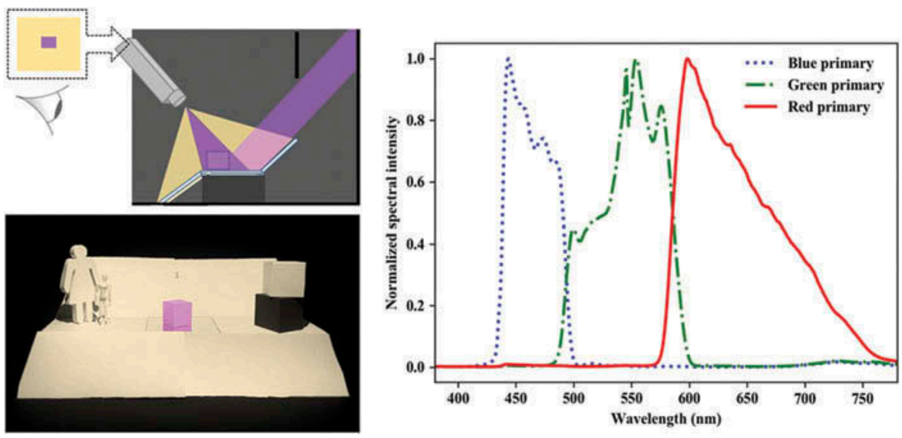

Fig. 1. (Top left) Schematic overview of the experimental setup. (Bottom left) Observer view of the scene for a purple starting position of the cube and a 4000 K illumination condition. (Right) Normalized spectra of the red, green, and blue primaries of the data projector.

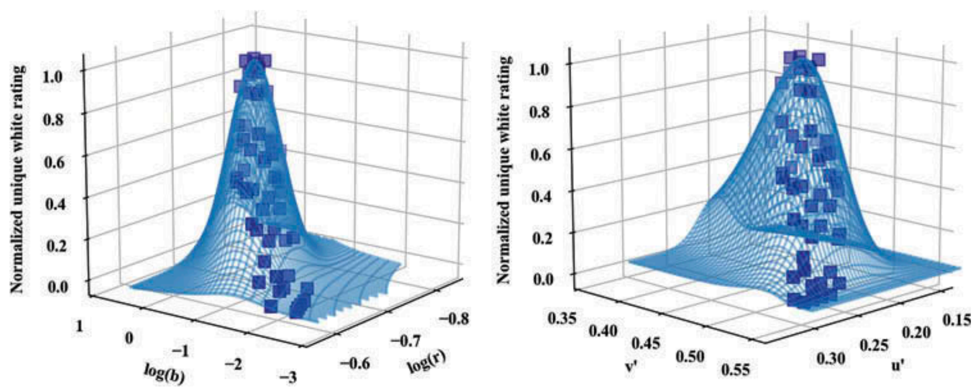

Fig. 2. Unique white ratings model fitted in the log-compressed (left) Macleod-Boytnon *r,b* chromaticity diagram and (right) back-converted to CIE *u'v'* coordinates.

two sets of tristimulus values of the memory color matches for the five familiar objects under each condition. For the 13 lighting conditions, this resulted in 156 sets of corresponding colors.

In the study, the performance of several chromatic adaptation models, sensor matrices, and formula for the degree of adaptation were tested using these sets. In addition, a *two-step von Kries chromatic adaptation transform* (CAT) was proposed in which the color under illumination A is first explicitly transformed to an illuminant-invariant state X_0 (which in CAT02 corresponds to the equi-energy white) and then further transformed to illumination condition B:

$$X_B{}' = \left(D_{B,0} \cdot \Lambda_{B\to 0} + \left(1 - D_{B,0}\right)\right) - 1 \cdot \left(D_{A,0} \cdot \Lambda_{A\to 0} + \left(1 - D_{A,0}\right)\right) \cdot X_A \tag{2a}$$

with

$$\Lambda_{A,B\to 0} = \frac{X_{w0}}{X_{wA,B}} \tag{2b}$$

and $D_{A,B\to 0}$ the degree of adaptation under illuminations A and B and $X_{w,i}$ (i: A, B, or 0) the sensor responses under the three respective illumination conditions. Compared to the commonly used one-step CATs that transform directly between illumination A and B, but for which the degree of adaptation is ambiguous to interpret when transforming between two colored illumination conditions, a two-step CAT has the advantage that it allows for a separate specification of the degree of adaptation under each illumination condition. As shown by Smet and others [2017a, 2017b], a two-step CAT was found to accurately predict corresponding colors obtained in these memory matching studies and those used for the development of various CAT sensor matrices (CIE16x-2004 [CIE 2004]) reported in the literature.

Note that the newly proposed update to the CIECAM02 color appearance model, CAM16, has picked up the two-step CAT approach. For more details on the two-step CAT, the reader is referred to Smet and others [2016, 2017a].

A two-step von Kries CAT, adoping Hunt-Pointer-Estevez sensor primaries, was used to obtain for each illuminant condition an effective degree of adaptation, D, by minimizing the Euclidean $u'v'$ color difference between CAT predictions and observer memory matches. Hunt-Pointer-Estevez sensors were used because they more closely correspond to cone responses than the sharpened CAT02 responses that suffer from a potential breakdown of predictions for very high chroma chromaticities [Brill and Süsstrunk 2008].

The optimized degree of adaptation D-values were then successfully modeled (R^2 = 0.87, *STRESS* = 13%) by a bivariate Gaussian function (1) in a log-compressed Macleod-Boyton (McB)-like chromaticity diagram [MacLeod and Boynton 1979]. Note that STRESS refers to the standardized residual sum of squares [Melgosa and others 2011]. The model takes into account the impact of light source chromaticity on the degree of adaptation (at least under L = 760 cd/m^2 background and dark surround conditions). As mentioned in the Introduction, given that the purpose of chromatic adaptation is to discount the illuminant—that is, make spectrally flat surface reflectances appear neutral—the degree of chromatic adaptation reflects the relative degree of neutrality: a spectrally neutral surface under colored illumination would appear neutral/white under complete adaptation but would increase in tint as the degree of chromatic adaptation decreases. Though achromatic settings are normally used to quantify color constancy or chromatic adaptation effects, in this study the tables are turned and chromatic adaptation has been used to quantify neutrality.

2.2. Derivation of neutral loci

2.2.1. UW-neutral locus

The neutral locus (line of whites) was derived from a bivariate Gaussian model (cfr. (1)) in the log-compressed Macleod-Boyton r,b chromaticity diagram fitted to the unique white ratings. The choice for the adoption of the log-compressed McB space, instead of directly using the $u'v'$ model already developed in Smet and others [2014], was inspired by the excellent fit achieved in Smet and others [2017b]. Indeed, a careful analysis showed that such as model is better able to predict the unique white ratings at lower CCTs (probably due to the saturation compression present in the $u'v'$ chromaticity diagram in the yellow–green to orange region near the spectrum locus). Plots of the model in the log-compressed McB space and in the CIE $u'v'$ chromaticity diagram are given in Fig. 2.

To derive a model for the UW-neutral locus in terms of the coordinates more commonly used in lighting science and technology—that is, CCT and Duv—the model was mapped by sampling the log-compressed McB space at 15 CCT_{10} and 25 Duv_{10} levels, respectively ranging from 2500 K to 20,000 K and −0.03 to +0.02; that is, for each CCT a set of 25 Duv levels was selected and the corresponding XYZ tristimulus values were calculated. CCT was sampled on a reciprocal scale (Mired scale) to have approximately equispaced CCT levels in the more perceptually uniform CIE $u'v'$ chromaticity diagram. (Note that the subscript 10 refers to the use of the CIE 1964 10° observer in the calculation of CCT and Duv.)

First, the neutrality model for the *luminance-invariant* case was applied to the log-compressed McB r,b coordinates of each sampling point, after which the Duv_{10} were determined that resulted in the largest *calculated degree of neutrality* ($Duv_{N,10}$) for each CCT_{10} level. Calculated degree of neutrality is the value obtained from (1) with parameter a_6 set to 1, effectively normalizing the experimentally determined unique white ratings to their maximum value. Results are plotted in Fig. 3.

In the u'_{10},v'_{10} chromaticity diagram, the UW-neutral locus can be described by

$$v'_{10}(u'_{10}) = \frac{0.5159 \cdot u'_{10} - 0.0952}{u'_{10} - 0.1812} \quad \text{for } (2500\ K \leq CCT \leq 20\,000\ K). \tag{3a}$$

The root mean square error (RMSE) and the coefficient of variation (R^2) for the $u'v'$ model are respectively 0.0026 and 0.998, indicating an extremely good fit (see also the dashed red line connecting the black dots in the left graph of Fig. 3).

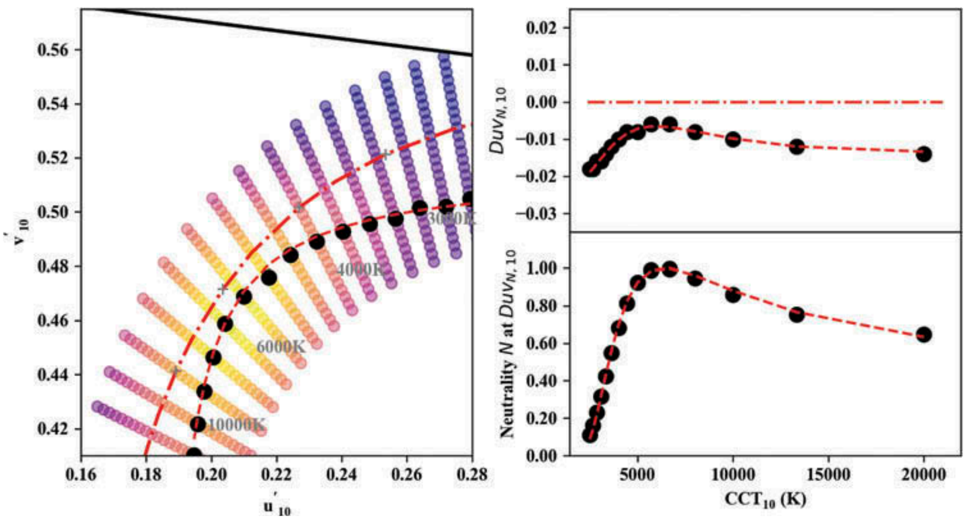

Fig. 3. UW-neutral locus model obtained from the unique white ratings of Smet and others [2014] (In all subplots: Data points of sampled neutral locus: black dots, model: red dashed line). (Left) (CCT, *Duv*) sampling (colored dots) of the CIE 1976 *u'v'* chromaticity around the Planckian locus (red dot-dash line). The color of the dots is indicative of the degree of neutrality (yellow: high/purple: low). (Top right) The most neutral *Duv* as a function of CCT (Planckian locus: red dot-dash line). (Bottom right) The degree of neutrality as a function of CCT.

The most neutral Duv_N as a function of CCT can be calculated as

$$\begin{aligned} Duv_D(CCT) = {} & 0.0202 \cdot \log(CCT/3325) \\ & \cdot \exp\left(-1.445 \cdot \log\left(CCT/3325\right)^2\right) \\ & + 0.0137. \end{aligned} \tag{3b}$$

The very good fit can again be seen in Fig. 3 (top right graph) and by the low RMSE (0.00051) and high R^2 (0.983).

Neutrality N as a function of CCT is given by

$$N(CCT) = \exp\left(-\left(6368 \cdot \left({}^1\!/_{CCT} - {}^1\!/_{6410}\right)\right)^2\right). \tag{3c}$$

The RMSE and R^2 are respectively 0.014 and 0.999.

2.2.2. CA-neutral locus

The same (CCT, *Duv*) sampling was used as that from the UW-neutral locus analysis. Again, for each sampling point the "degree of chromatic adaptation D" was calculated from its corresponding log-compressed McB r,b coordinates, after which for each CCT_{10} level the Duv_{10} values resulting in the largest *calculated degree of chromatic adaptation* ($Duv_{D,10}$) were determined. The results are plotted in Fig. 4.

In the u'_{10},v'_{10} chromaticity diagram, the CA-neutral locus can be described by

$$v'_{10}(u'_{10}) = \frac{0.5192 \cdot u'_{10} - 0.0983}{u'_{10} - 0.1882} \quad \text{for } (2500\ K \leq CCT \leq 20\,000\ K). \tag{4a}$$

The RMSE and the R^2 for the $u'v'$ model are respectively 0.00071 and 0.96, indicating an extremely good fit (see also the dashed red line connecting the black dots in the left graph of Fig. 4).

The Duv_D corresponding to the highest degree of adaptation D as a function of CCT can be calculated as

$$\begin{aligned} Duv_D(CCT) = {} & 0.0382 \cdot \log(CCT/2194) \\ & \cdot \exp\left(-0.679 \cdot \log\left(CCT/2194\right)^2\right) \\ & + 0.0172. \end{aligned} \tag{4b}$$

The very good fit can again be seen in Fig. 4 (top right graph) and by the low RMSE (0.001) and high R^2 (0.967).

The degree of adaptation D as a function of CCT is given by

$$D(CCT) = \exp\left(-\left(3912 \cdot \left({}^1\!/_{CCT} - {}^1\!/_{6795}\right)\right)^2\right). \tag{4c}$$

The RMSE and R^2 are 0.0089 and 0.998, respectively.

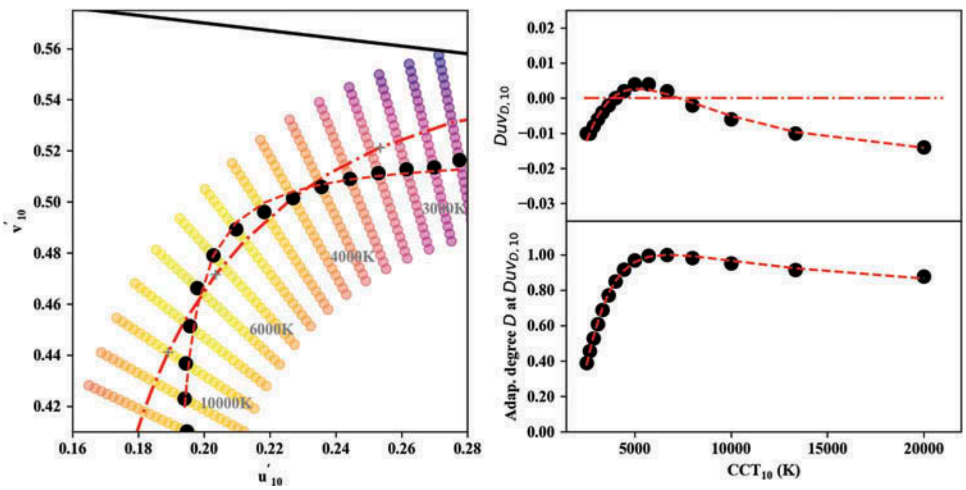

Fig. 4. CA-neutral locus model obtained from the modeled degrees of chromatic adaptation of Smet and others [2017b]. (In all subplots: Data points of sampled adaptation locus: black dots, model: red dashed line.) (Left) (CCT, *Duv*) sampling (colored dots) of the CIE 1976 *u′v′* chromaticity around the Planckian locus (red dot-dash line). The color of the dots is indicative of the degree of adaptation (yellow: high/purple: low). (Top right) The *Duv* with the highest degree of adaptation as a function of CCT (Planckian locus: red dot-dash line). (Bottom right) The degree of adaptation as a function of CCT.

3. Discussion

The substantial differences observed between the UW-neutral and the CA-neutral loci confirm the rather wide variation in lines of white [Li and others 2016; Ohno and Fein 2013; Ohno and Oh 2016; Perz and others 2016; Rea and Freyssinier 2014] and unique and preferred white chromaticities [Chauhan and others 2014; Choi and Suk 2016; Feng and others 2016; Honjyo and Nonaka 1970; Hurvich and Jameson 1951; Kuriki 2006; Priest 1921; Smet and others 2014; Sternheim and Drum 1993; Valberg 1971; Wang and Wei 2017] reported in the literature. (For an easy comparison, both *neutral* loci have been plotted in Fig. 5, together with several other white loci published in the literature.)

From Fig. 5 (left and top right) it is clear that the UW-locus is completely below the Planckian locus ($Duv < 0$), whereas the CA-locus also has a positive *Duv* between approximately 3800 K and 7300 K (Fig. 4, left graph). Despite this apparent disparity, the two loci do show a very similar but shifted behavior of *Duv* as a function of CCT (Fig. 5, top right), with a maximum *Duv* deviation of 0.012 at a CCT of 3770 K. The degree of neutrality as a function of CCT is also very similar for both loci but not identical. The small differences in the slopes on either side of the CCT corresponding to maximum neutrality are qualitatively consistent with a reduced degree of adaptation in the UW-rating experiments compared to that in the CA experiments due to a combined effect of smaller adapting field size (5.7° versus 50°; see, for example, Murray and others [2006]) and shorter adaptation times (order of a few seconds versus approximately a minute or more; see, for example, Fairchild and Reniff [1995]). The reduced adaptation leads to lower neutrality valuation at a given CCT or a smaller neutrality range at a given neutrality level. A steep rise and shallow decline at respectively low and high CCTs were also characteristic of Hurvich and Jameson's [1951] *white threshold contours* (see figure 3 in Hurvich and Jameson [1951]) and are furthermore in qualitative agreement with the increased degree of color constancy for neutral-to-bluish illuminations reported by Pearce and others [2014].

The maximum degree of neutrality (respectively the degree of unique white rating and chromatic adaptation) for both loci is found at CCTs of respectively 6410 K (Duv = −0.0066) and 6800 K (Duv = 0.0009). However, as also evident from the bottom right graph of Fig. 5, the differences in degree of neutrality within this range are extremely small (<0.0020) and substantially smaller (respectively 85% and 79%) than the RMSE values

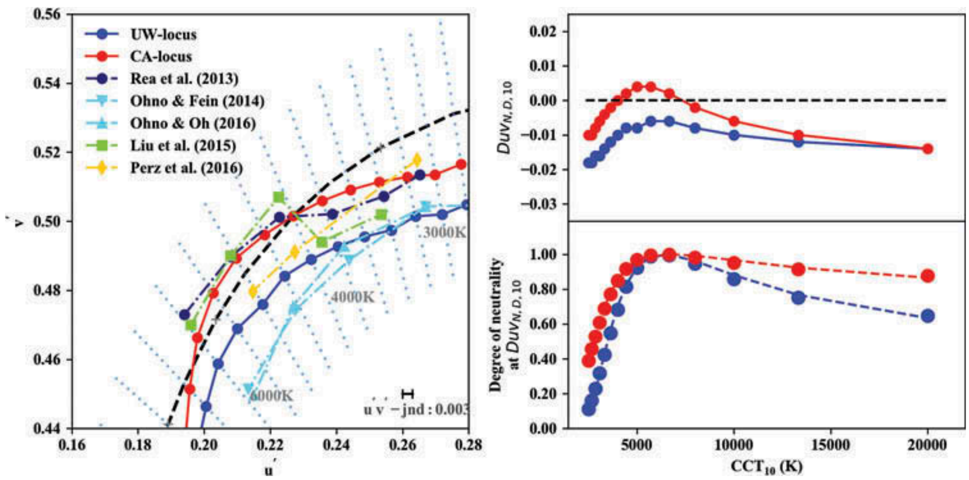

Fig. 5. Comparison of the UW-locus and CA-locus derived in this study. (Left) Comparison in *u'v'* chromaticity diagram. Other lines of white published in the literature have been plotted for comparison. (Top right) Duv_N and Duv_D as a function of CCT for the UW-locus (red) and the CA-locus (blue). (Bottom right) Normalized (maximum = 1) neutrality *N* and degree of adaptation *D* as a function of CCT for both loci.

for both neutral models. The CCT at maximum neutrality can therefore be well approximated by a single value of 6605 K, without incurring any large errors. The corresponding *Duv* values for the UW- and CA-loci are respectively −0.0067 and 0.0012. The CCT and *Duv* corresponding to maximum neutrality as derived from the degrees of adaptation (obtained using the memory color matches under neutral and colored illuminants) are therefore very close to those of D65 daylight (CCT_{10} = 6480 K, Duv_{10} = 0.0034), suggestive of earlier reports that vision processes such as color constancy and chromatic adaptation, and hence perceived illumination neutrality, are conditioned by natural scene statistics [Bosten and others 2015; Chauhan and others 2014; McDermott and Webster 2012; Panorgias and others 2012; Pearce and others 2014; Witzel and others 2011].

The steep change in degree of neutrality at low CCT, combined with the small shift ($\Delta E_{u'v'}$ = 0.0085) of the center of the bivariate Gaussian models (cfr. maximum neutrality) likely causes the more extended deviation (maximum ΔDuv = 0.012 at 3770 K) of the UW- and CA-neutral loci at lower CCTs. Kuriki and Uchikawa [1998] also reported shifts of unique white settings under dark adapted conditions compared to those made under (fully) adapted illumination conditions, even for highly reflective stimuli (dark stimuli tend to take on a hue complementary to that of the illumination, known as the Helson-Judd effect). Unique or neutral white therefore does not always appear to correspond to the colorimetric achromatic point; that is, the illumination chromaticity.

Another viable explanation for the observed discrepancy (*Duv* shift) between the UW- and the CA-locus, possibly related to the previous, might be the difference in appearance mode [Cuttle 2003]. Though the UW-neutral locus is more representative of the *object mode*, because it derived from unique white ratings of different colors presented on a real three-dimensional cube under dark adapted (no-adaptation) conditions, the CA-locus can be considered more characteristic of the *illumination mode* because it is based on the degrees of chromatic adaptation under various neutral and colored illuminations. Note that although observers also judged the color appearance of objects in the chromatic adaptation experiments, the derivation of the degree of adaptation effectively singled out (although there possibly was some impact of simultaneous contrast; Smet and others [2017b]) the illumination contribution to the whiteness perception of the stimuli. These two different modes of stimulus appearance can result in two different whiteness or neutrality perceptions through, for example, the enhanced whiteness perception associated with a slight purple or blue shift of object chromaticity [David and others 2013; Katayama and

Fairchild 2010; Katayama and others 2007; Vaeck 1979] or, as Grum and Patek [1965; p. 357] stated,

> It is evident that the apparent whiteness of a sample is dependent upon its chromaticness, i.e., a function of dominant wavelength and purity, and upon its luminous reflectance. A sample that is slightly yellow is judged to be whiter than a sample that is slightly red. A sample with a violet cast is considered whiter than one that has blue cast.

Finally, comparing the two neutral loci with those reported in the literature (see Fig. 5), it is clear that the CA-locus agrees strikingly well with the neutral loci obtained by Rea and Freyssinier [2013] and Li and others [2016]: Not only do they all have negative and positive *Duv*s for respectively low and high CCTs but they also seem to cross the Planckian locus at pretty much the same CCT (3800 K) and have very similar maximum distances from the Planckian locus (absolute *Duv*) in both low and high CCT regions. The good agreement is consistent with all three loci being highly driven by pure adapted illumination chromaticity (see discussion above): Rea and Freyssinier [2013] used an illumination box with a large field of view, Li and others [2016] used an immersive full room setup, and, as explained earlier, the CA-neutral locus is based on degrees of chromatic adaptation. It is worth noting that using an ambient lighting setup Choi and Suk [2016] also found a range of whites with positive *Duv* at high CCTs. Perz and others [2016] also used an illumination box but, as mentioned by the authors themselves, the presence of a white sheet of office paper in the box might have affected their results because observers had more than one stimulus to judge white perception. Interestingly, a good part of their white locus lies approximately midway between the UW- and CA-loci, suggestive of white perception having been based in part on an illumination mode and in part on an object mode. At lower CCTs, however, their result are in quite good agreement with the CA-locus and the white loci of Rea and Freyssinier [2013] and Li and others [2016].

As for the UW-locus, it is clear from Fig. 5 that it is in good agreement with the *natural locus* of Ohno and Fein [2013] and Ohno and Oh [2016] (and that reported by Perz and others [2016]) for mid-range to low CCTs but that at higher CCTs the two diverge. This is likely due to Ohno's locus actually corresponding to perceived naturalness of the illumination, rather than illumination neutrality. As already mentioned in the Introduction, some authors [Wang and Wei 2017; Wei and Houser 2016] have also indicated that color rendition issues, such as increased color gamut, could have had an impact on the the results of Ohno et al. [2013, 2016].

4. Conclusions/summary

In the literature, several white loci or lines of white have been reported by various authors. These white loci are lines that have typically been investigated by determining for several CCTs the *Duv* resulting in the most neutral (achromatic), most natural, or most preferred whiteness perception. Like studies on single achromatic chromaticities, there is substantial discrepancy between the shape and location of these neutral loci, either due to differences in experimental or viewing conditions or because of differences in the concept of white (achromatic, natural, and preferred whites are not necessarily identical).

In this article, two additional new neutral loci were derived based on psychophysical data from two quite diverse studies published in literature. The UW-neutral locus is based on the unique white ratings obtained on a real three-dimensional cube viewed under dark adapted conditions [Smet and others 2014]. The CA-neutral locus is based on the modeled degrees of chromatic adaptation obtained from a study where chromatic adaptation under neutral and highly colored illuminations has been investigated using memory color matches [Smet and others 2017b]. For each neutral locus, equations were derived describing their location in the CIE 1976 *u*'*v*' chromaticity diagram, as well as formula to predict the most neutral *Duv* and the degree of neutrality as a function of CCT (often ignored in other lines of white studies reported in literature).

Although the two new loci were not identical, they were very similar in shape, with one seemingly a shifted version of the other, with as likely causes differences in adaptation state and appearance mode.

The CA-neutral locus was in very good agreement with other illumination-based neutral white loci [Rea and Freyssinier 2013; Li and others 2016], which all seem to have negative *Duv* for lower CCTs and positive *Duv* for higher CCTs. The UW-neutral locus, on the other hand, was located completely below the Planckian locus, which is consistent with the *natural white locus* of Ohno and Fein [2013] and Ohno and Oh [2016]. However, its location was only in close agreement at mid-range to low CCTs. These differences are likely due to differences in the concept of white that each locus describes but could also have been caused by differences in viewing conditions (a dark, spectrally neutral surround versus a fully immersive, illuminated surround) and the potential impact of color rendition on the results of Ohno et al. [2013, 2016].

As a final comment, the two new white loci derived in this article will hopefully stimulate further research on on- and off-Planckian light sources, in particular the impact of adaptation states, viewing conditions, and appearance modes, as well as provide additional quantitative and qualitative valuable information characterizing whiteness perception of illumination color for use by lighting professionals in guiding light source development and selection.

Funding

The author is supported by a Postdoctoral Fellowship of the Research Foundation Flanders (FWO) (12B4916N, "Color Appearance in Neutral, Colored and Spatially Complex Backgrounds").

Disclosure statement

No potential conflict of interest was reported by the authors.

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